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Booth

An acoustic pyrometer.

1912
L64

AN ACOUSTIC PYROMETER

BY

HARRY TYLER BOOTH

B. S. Carleton College, 1915

THESIS

Submitted in Partial Fulfillment of the Requirements for the

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY HARRY TYLER BOOTH

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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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- CHAPTER I -

- INTRODUCTION AND THEORY -

- INTRODUCTION -

Temperature may be measured by the variation of physical properties of a substance with the temperature. As examples we have the mercury-in-glass and gas thermometers depending for their indications upon the property "expansion". Resistance thermometers and thermocouples are dependent upon the change in their electrical properties as the temperature changes. Very high temperatures are measured by radiation pyrometers which depend on the change in the radiating powers of the substance.

Other properties have been investigated for the purpose of basing a temperature measuring instrument upon them. The velocity of sound, for instance, varies simply and continuously with the temperature, and various attempts have been made to utilize this variation as a temperature indicator. It has been the purpose of this investigation to extend these researches with the velocity of sound, and to determine the possibilities for its use as a thermometric property.

- THEORY -

The velocity of sound, in an acoustical thermometer, is not measured directly, but in terms of quantities which are proportional to it: that is, in terms of wave length and pitch according to the relation

$$V = N \beta \text{ -------------------------- (I)}$$

where

V = velocity of sound,

N = frequency of the tone,

β = wave length of the tone.

NOTE.- It is customary to use the letter λ for the wave length, but throughout this report the letter β will be used.

The variation of the velocity with the temperature is given by the equation

$$V_I = V_0 \sqrt{I + \alpha T_I} \quad \text{---------------(2)}$$

where

T_I = the Centigrade temperature at which V_I is observed.

V_0 = the velocity at 0° Centigrade.

α = I/ 273

So, combining equations I and 2,

$$N_I \beta_I = V_0 \sqrt{I + \alpha T_I} \quad \text{--------------(3)}$$

And similarly,

$$N_2 \beta_2 = V_0 \sqrt{I + \alpha T_2} \quad \text{--------------(4)}$$

the subscripts indicating the proper combination of the terms at different temperatures.

Now, squaring, and dividing (3) by (4), we obtain

$$\frac{N_I^2 \beta_I^2}{N_2^2 \beta_2^2} = \frac{V_0^2}{V_0^2} \frac{(I + \alpha T_I)}{(I + \alpha T_2)} \quad \text{----------------------(5)}$$

or,

$$N_2^2 = N_I^2 \frac{\beta_I^2}{\beta_2^2} \frac{(273 + T_2)}{(273 \ast T_I)} = N_I^2 \frac{\beta_I^2}{\beta_I^2} \frac{\theta_I}{\theta_2} \quad \text{-----(6)}$$

where β_I and θ_2 are the absolute temperatures.

In this investigation, the foregoing theory is applied to the case of a cylindrical tube closed at one end, it being assumed that, to a first approximation, the velocity of the sound wave is not affected by the walls of the tube.

The sound waves pass thru the tube until they reach the closed end, where they are reflected back upon themselves, so that stationary waves are set up. Experimentally, two cases are to be considered: first, when the frequency of the tone is kept

constant, and second, when the wave length of the tone is kept constant.

CASE I.- N = a constant.

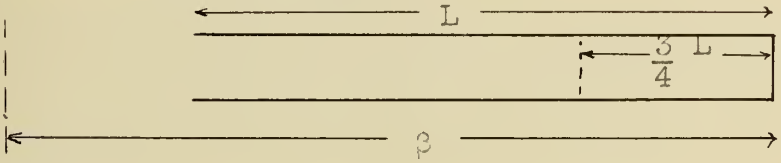
We know that

$$V = N\beta = V_0\sqrt{I + \alpha T} = K\sqrt{\theta} \text{ -----(7)}$$

and that

$$L = \frac{3}{4}\beta \text{ ---------------------------------(8)}$$

for the first overtone, where L = the length of the tube, and K in equation (7) is $V_0 / \sqrt{273}$.



Now, as the temperature rises, the relation between the length of the tube and the temperature is obtained by substituting the value for β given in equation (8) in place of β in equation (7), which gives

$$L = \frac{3}{4}\frac{V_o}{N}\sqrt{I + \alpha T} = k\sqrt{\theta} \text{ ---------(9)}$$

Hence, L varies as the square root of the absolute temperature, since V_0 is a constant, and N in this case is assumed to be constant. Therefore, temperature might be measured by observing the rate of change of L with θ, obtaining the maximum resonance for each temperature. That is, adjust L according to the relation

$$L = \frac{3}{4}\beta$$

- CASE 2 -

$$\beta = \frac{4}{3}L = \text{a constant.}$$

Since β is a constant in this case, and equation (6)

applies generally, by cancelling the ratio between the β's in equation (6), we have left

$$N_2^2 = N_I^2 \frac{\theta_I}{\theta_2} \text{ ------------------------(IO)}$$

This last case, where the pitch is varied with the temperature in order to have the tube of constant dimensions respond to its first overtone at every temperature, was the one chosen for investigation.

- CHAPTER 2 -

- HISTORICAL -

In I873 Professor A.M. Mayer proposed that the velocity of sound might be used as a means of measuring temperature, but no experiments were performed to test his theory.(I)

Preston suggested in I89I that temperature be measured either by a tube of constant dimensions, subjected to a source of heat, emitting a tone of a variable pitch, whose frequency could be determined by comparing with a tuning fork or, by a tube of variable length emitting a tone of constant pitch. In either case, the tones of the tuning fork and the tube would be adjusted for unison. His proposal was based on the theory that the pitch of the tone emitted by a tube of constant length varies as the square root of the absolute temperature: and when the length is variable, as the square of the length.(2)

In I893, F.Sanford tested Prestons theory, with, however, no great refinement of apparatus. This consisted of a brass tube closed at one end with a brass plug. Another smaller brass tube was fixed to the larger one in such a way that when a stream of air was forced thru it, a musical tone was emitted by the larger tube. His results indicated that Prestons theory was correct, namely, that upon heating the sounding tube, the note given forth when the tube is blown, varies as the square root of the absolute temperature. The temperatures in his work varied from 0° C to 80° C and the calculated temperature differed from the actual temperature of the tube, as observed with a thermometer, by several percent. The discrepancy was apparently due to the difficulty experienced in measuring the pitch of the blown tube with sufficient accuracy.(3)

(I) - " On an Acoustic Pyrometer". A.M.Mayer. Phil.Mag. XLV,I8,I873 (See Rayleighs "Theory of Sound" Vol.II,P.30).

(2) - Preston, Phil. Mag. for July, I89I.

(3) - " AnAcoustic Pyrometer", F.Sanford. Phys. Rev. I,I40,I893.

In 1897, Quincke carried out a series of experiments in which he measured temperature by observing the variation of the wave length in a tube, when the pitch of an external source of sound was kept constant and the temperature of the tube varied.

His apparatus consisted of a cylindrical tube, closed at one end, which he called the resonator. It was placed so that it could be heated uniformly and thermometers and thermocouples were used for measuring the actual temperature. He had an external source of sound whose pitch was kept constant, and determined the wave length in the heated tube by finding the distance between two points of maximum or of minimum intensity inside the tube. This was done by inserting a long thin cylinder to which a rubber tube leading to the observers ear was connected, into the resonator and noting the points of maximum and minimum intensity. From these observations, the wave length could be calculated. Temperatures between 0° C and 750° C were tested, the observed and calculated temperatures checking within the limit of experimental error. Apparently, the highest temperature measured with a thermometer was approximately 500° C, the temperatures above that being calculated from wave length alone.(4)

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(4) - "An Acoustic Thermometer for High And Low Temperatures". G.Quincke, Ann. d. Phys. u. Chem. 63,page 66, 1897. (This article is written in German).

("Ein akustisches Thermometer für hohe und niedrige Temperaturen").

- CHAPTER 3 -

- EXPERIMENTAL -

- STATEMENT OF THE PROBLEM -

The variation of the velocity of sound with the temperature was tested in the following manner:

A tube of given dimensions responds or " resonates" at a given temperature to a certain definite pitch. If the temperature is changed, the resonator will respond to a different pitch, the pitch varying, according to the theory developed, directly as the square root of the absolute temperature. By determining the point of resonance, and simultaneously measuring the temperature, the experimental relation between the pitch and the temperature may be ascertained. Once this is done, if conditions remain the same, the temperature may be determined by observations on the frequency alone.

The resonance point may be determined by observing the deflections of a Rayleigh disc(5) suspended at a loop in the closed tube. The deflection will be a maximum when the tube is in resonance with the external source of sound. This will be explained in more detail a little later.

So the problem is to determine experimentally the relation between pitch and temperature as applied to a resonance tube closed at one end. The manner in which this was done will be shown, the apparatus used and the results obtained being described in this chapter.

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(5)- a) "On an Instrument Capable of Measuring thr Intensity of of Aerial Vibrations" Lord Rayleigh,Phil.Mag. XIV,pp I86 and I87, I882. (Also "Scientific Papers, Vol.II,pp. I32.

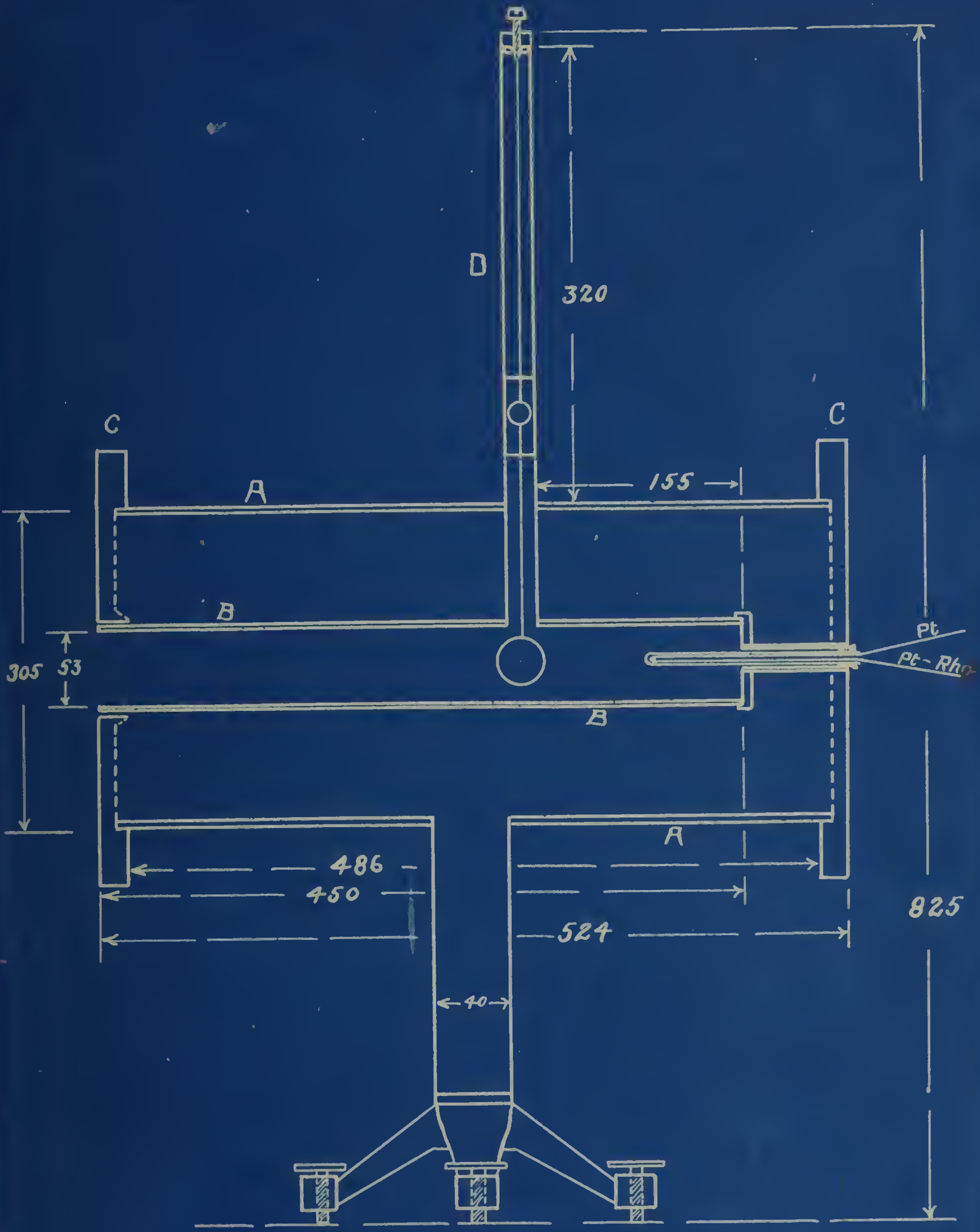
b) Rayleigh,"Theory of Sound",Vol.II, pp. 44-45.

- APPARATUS -

THE RESONATOR.- The resonator itself (BB Fig.I.) is a cylindrical wrought iron tube closed at one end with an iro screw cap. As shown in Fig.I, it is firmly fixed to the center of an eight inch steel tube (AA Fig.I). This outer tube forms a substantial covering for the thermal insulation which is packed between the walls of the two tubes. The ends of the outer tube are covered with iron caps, the open end of the resonator being flush with the outer surface of the cap. The whole instrument is supported on an iron pedestal which is suitably and conveniently arranged for leveling.

A 3/4 inch iron pipe (D Fig.I), 40 centimeters long, is screwed into the top of the resonator tube. A light phosphor bronze strip is fastened to a hard rubber plug placed in the upper end of the pipe, and extends down about 25 cms, where it is fastened to what we shall call the "suspension unit". This unit consists of a thin circular mica disc firmly fixed to one end of a stiff copper wire about I4 cms. long,at the other end of which is a light plane mirror. The unit is fastened to the phosphor bronze strip by a small screw immediately above the mirror. (Fig.I). Thus any motion given to the mica disc in the center of the resonator, is transmitted entirely to the mirror, and may be observed.

A window was cut thru the suspension tube immediately in front of the mirror to allow the deflections to be observed with a telescope and scale. A piece of heavy plate glass was placed over this window and any cracks around it were made air tight with asbestos paste, to eliminate convection currents in the perpendicular tube. A hollow plug having a small hole thru the center for the copper wire to pass, was placed in the tube below the



ELEVATION OF [illegible]

DIMENSIONS IN MILLIMETERS

[illegible] NO. 1

window for the same reason. The suspension was soldered to a brass adjusting screw passing thru the hard rubber plug at the upper end of the suspension tube.

It was by means of this suspended disc that the maximum resonance point was determined, according to the theory advanced by Rayleigh and Koenig. (6(If a flat disc is suspended in a moving fluid, it will experience a turning moment , the value of which is given by the expression

$$M = 4/3\ \delta\ a^3\ W^2 \sin 2\theta$$

where δ = the density of the fluid,
a = the radius of the disc,
W = the velocity of the stream,
θ = the angle between the normal on the disc and the direction of flow.

Sound waves give alternating currents instead of a continuous flow, so that the mean square velocity is taken .

Since the disc is suspended at a loop I/3 the length of the tube from the closed end, it will experience a maximum deflection when resonance occurs since the velocity of the air is greatest at a loop.

The couple exerted by the moving fluid on the disc is in such a direction that the disc is turned with its flat side perpendicular to the motion of the stream : the angle θ is decreased.

Also, since the position of the disc is fixed,and a maximum deflection

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(6) Ann. d. Phys. u. Chem. Walter Koenig, 43, I89I. page 43.

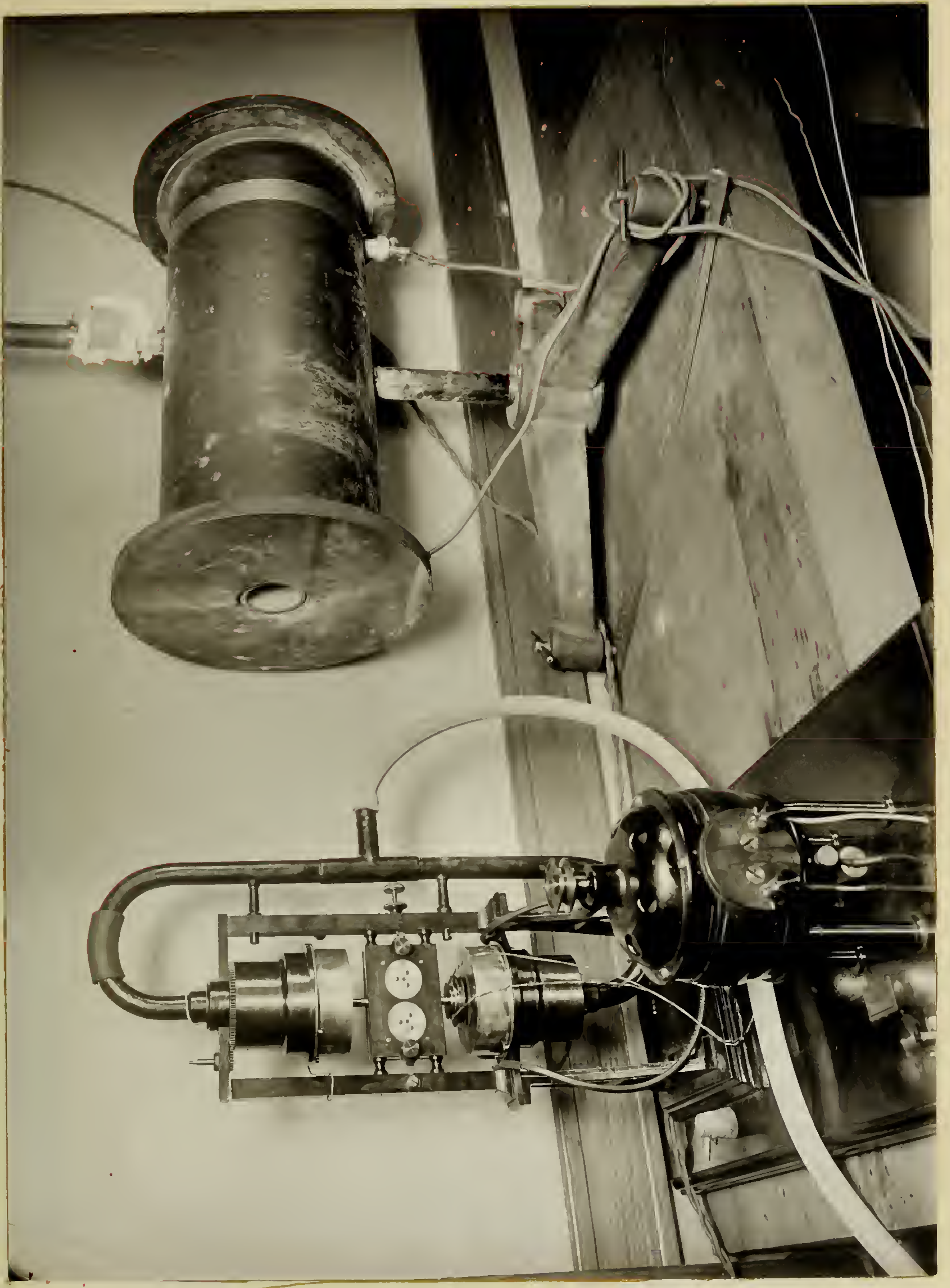


FIGURE 2

THE RESONATOR AND SIREN

is obtained for each determination, our assumption that the wave length of the tone is (a constant is) justified.

METHOD OF HEATING THE RESONATOR.- Since the relation between pitches and temperatures between the limits 26° C and I000°C was desired, some method had to be devised for obtaining the higher temperatures. It was finally decided to follow the electric furnace idea, and so a large number of turns of number I4 Nichrome wire were placed around the resonator tube. Several layers of asbestos paper were first wrapped around the tube and fastened firmly while the heating coil was being wrapped about it. Immediately surrounding the heating coil was placed a covering of asbestos paste and powder, the remaining space between the two tubes being filled in with asbestos powder and pipe insulation. The coil terminals are led out thru two porcelain tubes to the binding posts. One of these is shown in Fig.2. which is a photograph of the instrument as diagrammed in Fig.I.

The EXTERNAL SOURCE OF SOUND.- Several instruments for generating the resonating tone were tried. These included tone variators, tuning forks, a Koenig siren, and a Helmholtz double siren. This last proved to be the most satisfactory, since the pitch could be regulated exactly, and easily determined without depending upon any calibrations, and also because the intensity of the tone could be varied. A decided objection to the tone variators was that at the higher pitches, the intensity of the note fell off to such a degree that it was very difficult to determine the maximum deflection. This siren is seen at the left of the resonator in Fig.2.

TEMPERATURE MEASUREMENTS.- After experimenting with mercury and resistance thermometers, a platinum,- platinum-rhodium thermocouple in connection with an Otto Wolff potentiometer was selected to measure the temperature of the resonator tube.

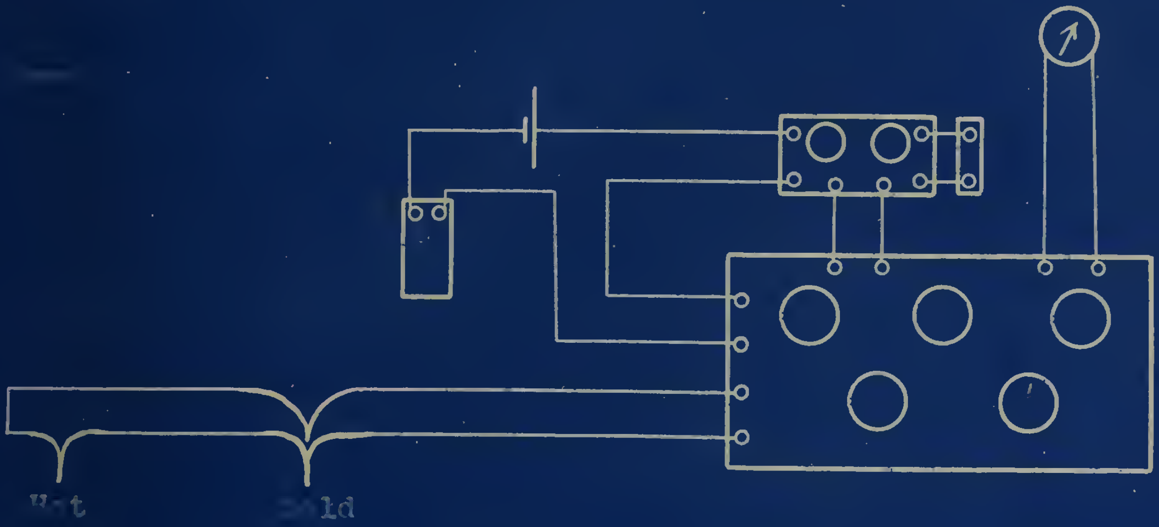


DIAGRAM OF POTENTIOMETER CIRCUIT

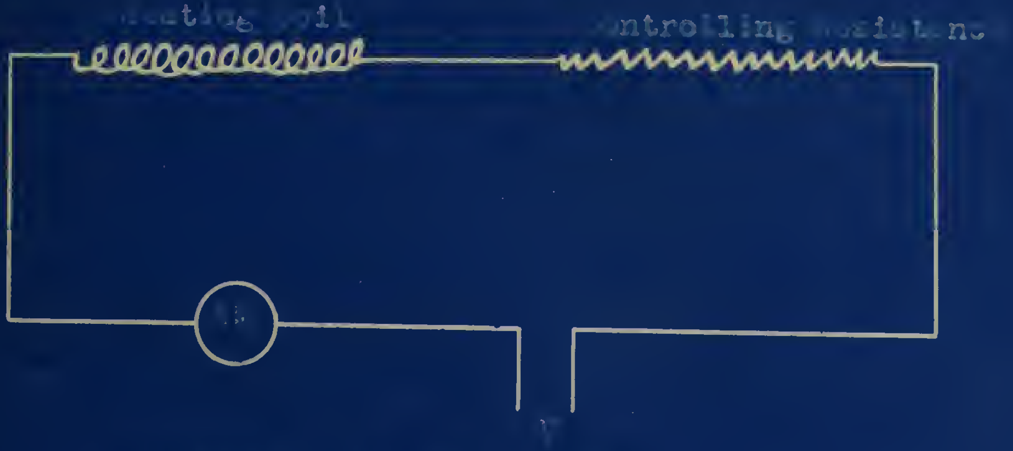


DIAGRAM OF HEATING CIRCUIT

FIGURE No.3

The hot junction of the thermocouple, suitably insulated, was placed in a quartz tube and inserted into the resonator. (Fig.I) The cold junction was supported in a glass tube and kept at room temperature thruout the series of readings. The potentiometer is made for thermocouple work, and is thermally insulated with heavy hard rubber wherever it must be touched. This is to elimanate stray currents due to unequal heating.

A Leeds and Northrup Low resistance galvanometer in connection with a telescope and scale was used to indicate when the electromotive forces were balanced. With this intrument, electromotive forces as low as .OI microvolts could be detected, altho for this investigation it was unnecessary to determine the temperature closer than one tenth of a degree Centigrade.

The standard electromotive force was supplied by a certified Weston Standard Cell.

A battery of five storage cells was used to furnish the current thru the potentiometer; and to make this as constant as possible, they were connected in parallel.

Figure 3 shows the electrical connections of the heating circuit, and also of the potentiometer circuit.

Figure 4 shows a general view of the whole set of apparatus.

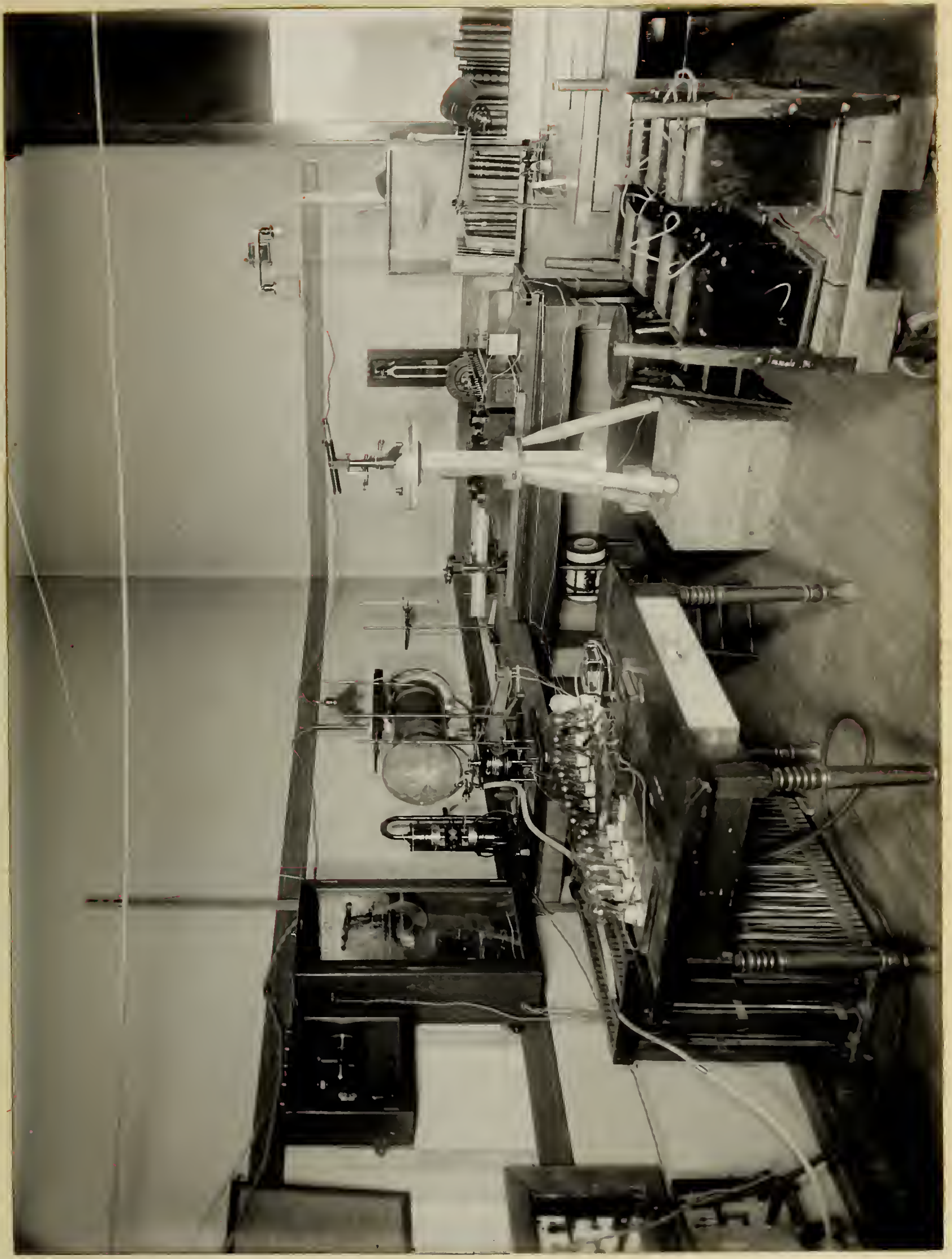


FIGURE 4

GENERAL VIEW OF THE APPARATUS

PROCEDURE.- Simultaneous values of temperature and pitch were measured, the coincidence of the two quantities being indicated by the maximum deflection of the resonator mirror, That is, when the temperature and pitch were "coincident", the tube resonated, this being in accordance with the condition that the wave length remain constant.

To repeat observations under essentially similar conditions, the temperature was brought to a constant value before any measurements were taken at that temperature. This was obtained by setting the heating current at a fixed value and allowing it to flow until a condition of equilibrium was attained. When the potentiometer indicated a change of not more than I° C per minute, the pitch of the siren was adjusted until a maximum deflection of the resonator mirror was obtained. The potentiometer was then read as quickly as possible. Usually it was possible to obtain several readings while the temperature was changing two or three degrees. If the variation was more than this, the readings were rejected.

The value of the pitch was obtained by observing the number of revolutions made by the siren disc during I5 seconds, and calculating the frequency from the speed and number of holes in the disc. A counting device on the siren axle allowed the speed to be taken with precision. A stop watch was used throughout the experiment. It was estimated that the pitches were determined with a maximum error of two vibrations per second at the higher frequencies, and about one vibration per second at the lower pitches. This corresponds to a .2 per cent error throughout the range covered.

The temperature was read to tenths of a degree on the potentiometer.

RESULTS.- In Figure 5, the relation between N^2 and θ is shown. It is obvious from the form of the equation that the curve should be a straight line. The method of calculation of Table 5 is shown on page 20. If N were plotted against θ, the curve would be a parabola, but since the portion we are interested in is so far from the origin, it would be almost a straight line. In fact, the $N^2 - \theta$ curve differs very little from the $N - \theta$ curve. Altho the relation involves the absolute temperature θ, Centigrade temperatures were plotted, as the θ curve differs from the T curve only by a constant.

The results shown in Tables 6 and 7 were obtained when a mercury thermometer was used to measure the temperature of the resonator tube. The resonating tone was supplied in these as well as all the following work with the Helmholtz double siren.

Figures 8,9 and IO with the accompanying tables, were obtain- when a platinum platinum-rhodium thermocouple was used to measure the resonator temperature. The electromotive force readings were in every case reduced to temperatures by comparison with the calibration curve for the thermocouple. This was obtained at an earlier date by calibrating the couple against the melting points of Zinc, Copper, Silver, and the steam point. The calibration was checked, and found to hold exactly.

The dotted line in Figures 7,8,9, and IO is the theoretical curve given in Figure 5, drawn as a reference line for the comparison with the experimental curves.

Table II shows the range of pitches of the tones obtainable on the Helmholtz siren. A continuous change in the pitch from 360 to II25 vibrations per second could be obtained, and the intensity could be varied by varying the air pressure.

- TABLE NO. 5 -

N	N^2	T
555	307500	25
62I	385000	I00
698	488000	200
768	59I000	300
834	694000	400
894	798000	500
950	90I000	600
I000	I000000	700

The above table is calculated from the equation

$$\frac{N_I^2}{N_2^2} = \frac{\theta_I}{\theta_2}$$

which was developed in the theory. The way in which the above values were determined was this: the pitch to which the resonator would respond at room temperature was determined. This was found to be 555 vibrations per second, and the room temperature was 25° C. Hence N_I and θ_I may be considered as constants of the instrument, and the formula reduces to

$$N_2^2 = N_I^2 \frac{\theta_2}{\theta_I} = \frac{307500}{298} (273 + T_2)$$

In this formula, T is the independent variable, and N the dependent.

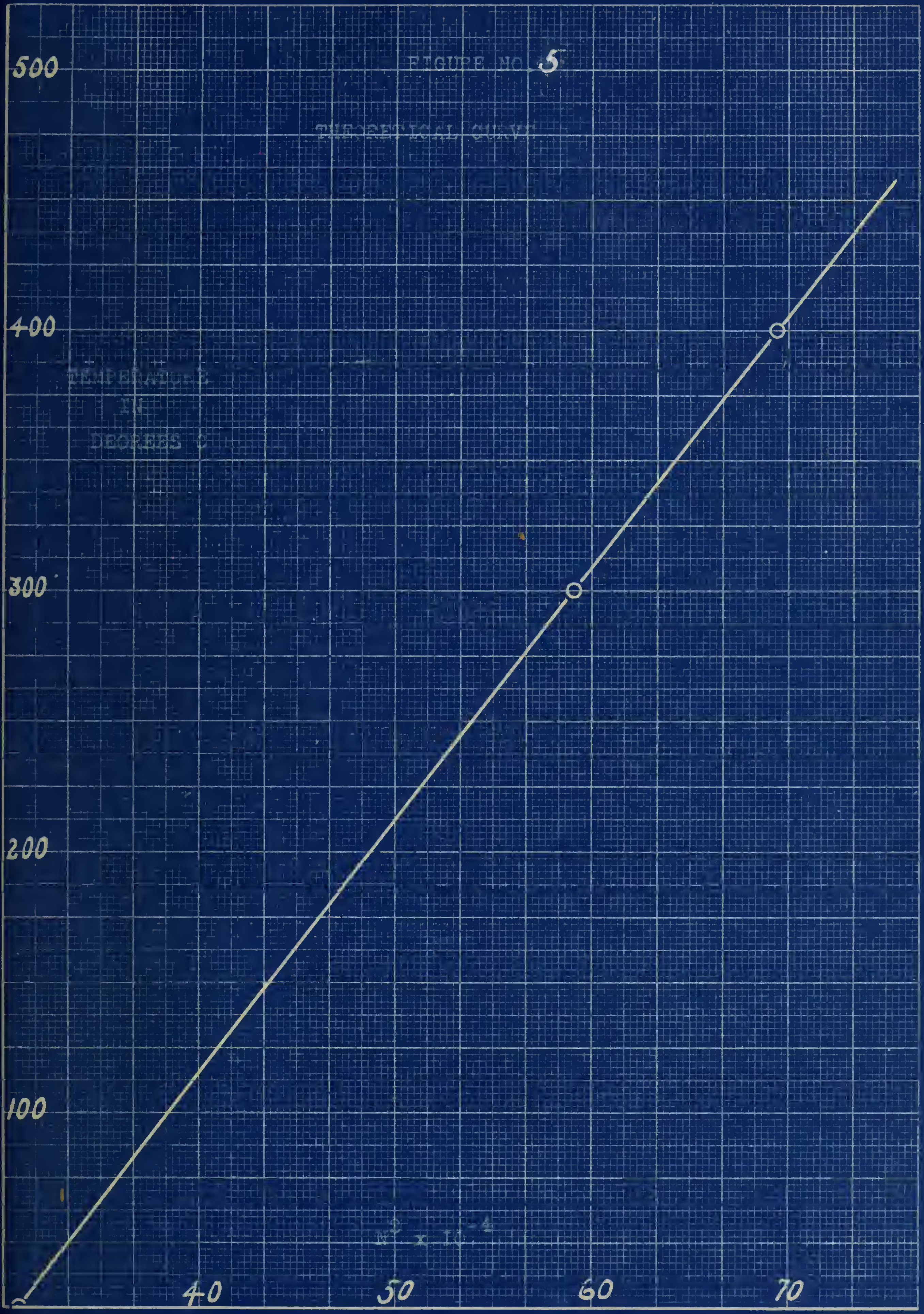


FIGURE NO. 5

THEORETICAL CURVE

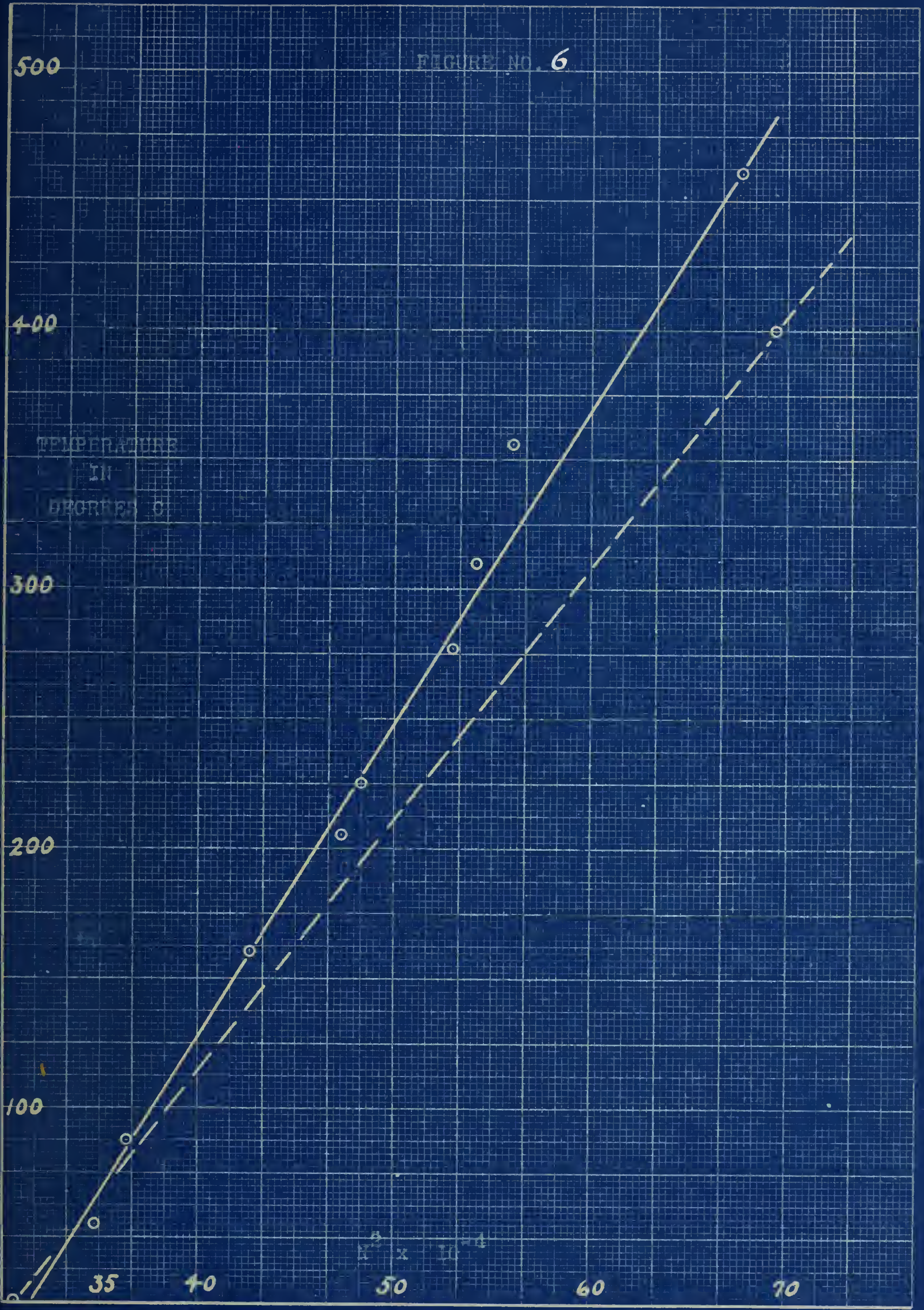
Lloyde's University Store—1915

- TABLE NO. 6 -

R P M	A	N	$N^2(10^{-3})$	T
3270	10	545	297	25
3540	10	590	348	60
3626	10	604	364	88
3270	12	654	426	162
3440	12	688	473	206
2590	16	691	477	247
2630	16	700	490	245
2730	16	728	530	280
2760	16	736	541	310
2870	16	749	560	356
3083	16	822	776	462

The above observations were taken using a mercury bulb thermometer to measure the resonator temperature, and with the Helmholtz double siren supplying the resonating tone.

The second column headed "A" means the number of holes in the siren disc. This inconnection with the revolutions per minute is sufficient data with which to calculate the pitch of the note. In all the following tables where the symbol "A" appears at the head of a column, it has the same significance. N is in vibrations per second, and T is in degrees Centigrade.



- TABLE NO. 7 -

R P M	A	N	$N^2(I0^{-3})$	T
3330	I0	555	307	35
3380	I2	674	454	I96
3560	I2	7I2	506	265
3740	I2	748	560	3I5

These results were also taken with a mercury thermometer in the same manner as Table No. 6.

- TABLE NO. 8 -

R P M	A	N	Microvolts	$N^2(I0^{-3})$	T
3294	I0	549	5	30I	25
33I0	I2	662	I299	437	205
3466	I2	693	I837	480	263
3702	I2	740	2870	546	374
3II0	I5	778	3694	605	460
27I0	I8	8I3	4350	660	525
2760	I8	828	48II	686	572

Starting with the results shown in Table No.8, all the subsequent data were taken using a platinum platinum-rhodium thermocouple to determine the temperatures, and the Helmholtz siren as before to determine the pitches. The electromotive force readings were reduced to temperatures by means of a calibration curve taken against the fixed points. (Cu, Zn, Ag, Water boiling)

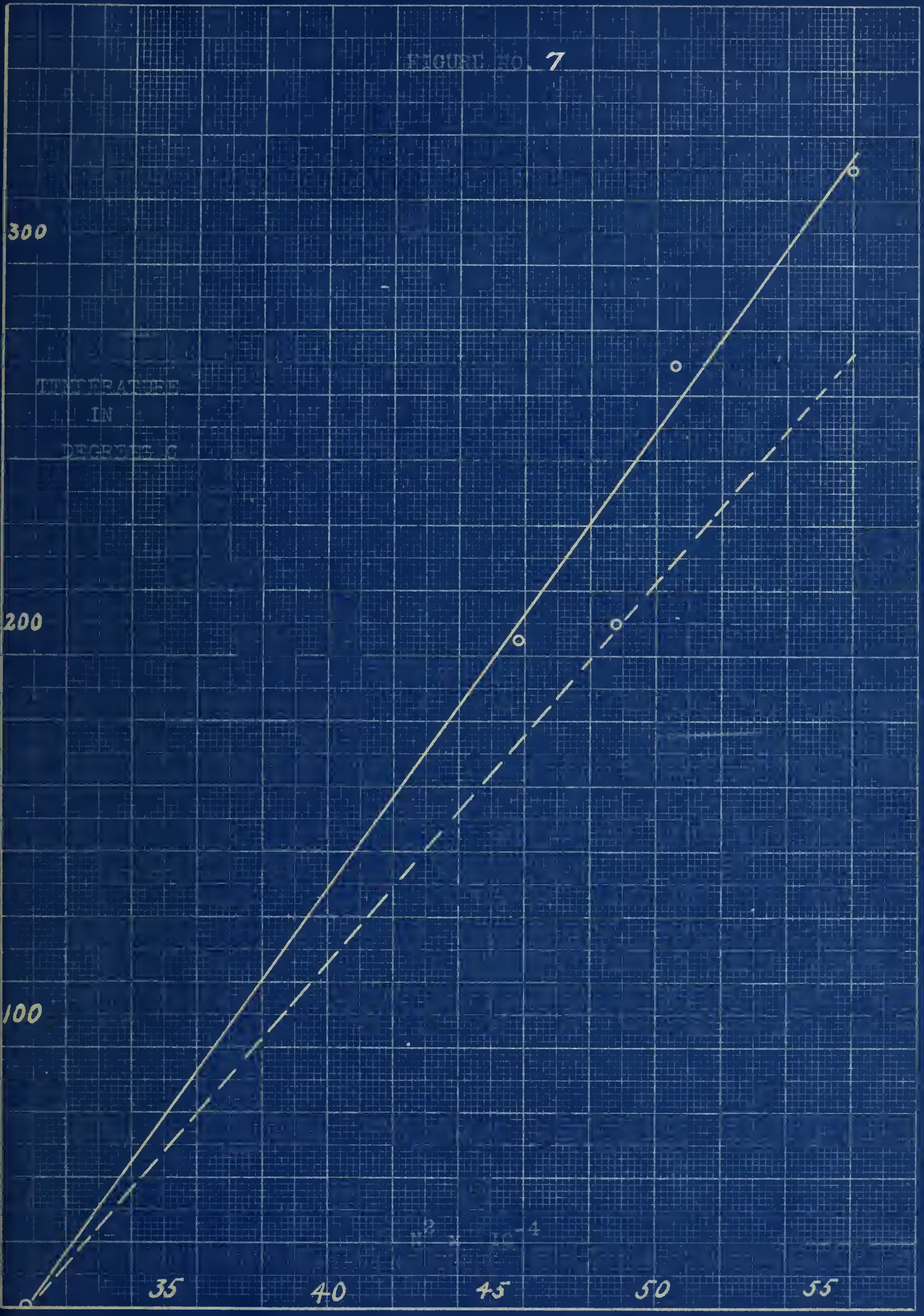


FIGURE NO. 7

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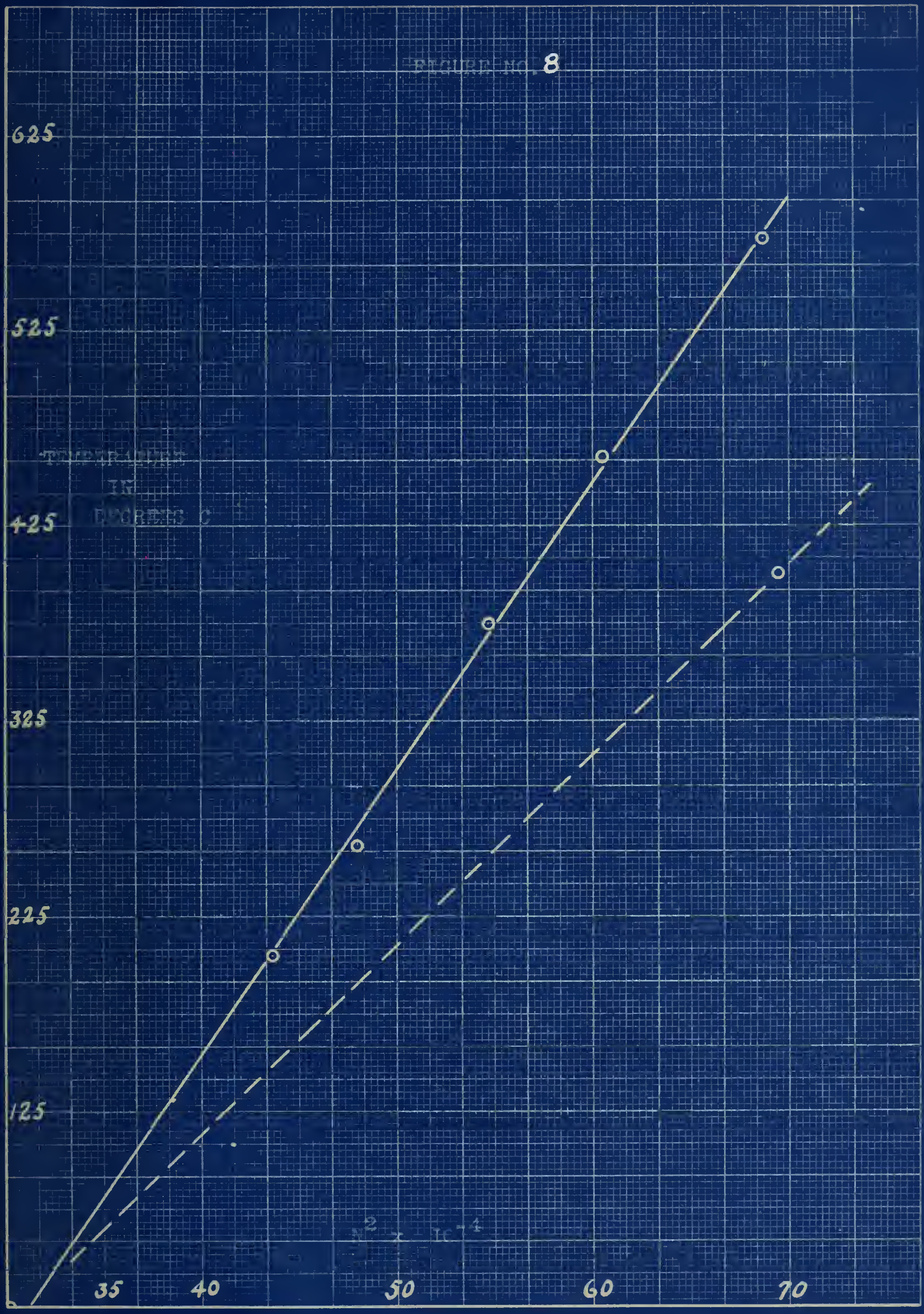


FIGURE NO. 8
625
525
425
325
225
125
TEMPERATURE
IN
DEGREES C
35
40
50
60
70
$N^2 \times 10^{-4}$

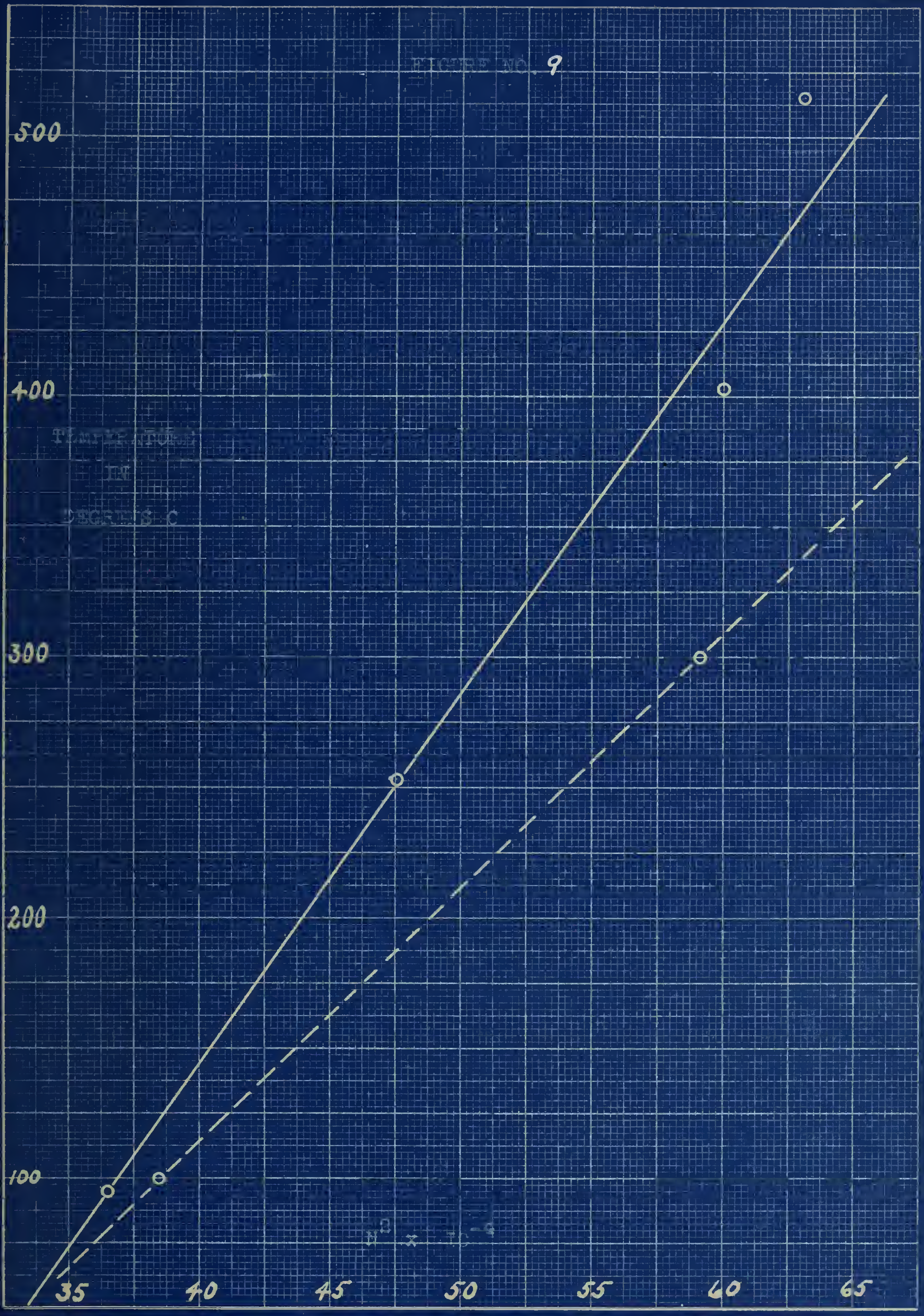
- TABLE NO. 9 -

R P M	A	N	Midro volts	$N^2(IO^{-3})$	T
3020	I2	604	584	365	95
3450	I2	690	I795	476	256
3I00	I5	775	3I94	600	406
3I80	I5	795	4288	632	5I7

- TABLE NO. IO -

3335	IO	556	3	309	25
3568	IO	595	4I9	353	85
3926	IO	654	I098	428	I80
3074	I5	769	2947	590	380
2776	I8	833	4327	694	522
3084	I8	925	6227	855	705
3276	I8	983	8458	967	9I4

The data in Tables 9 and IO were taken under practically the same conditions as No.8, that is a Pt Pt-Rho thermocouple was used to measure the temperature of the resonator, and the Helmholtz siren was used to determine the pitches. The column headings of No.9 hold for No.IO also.



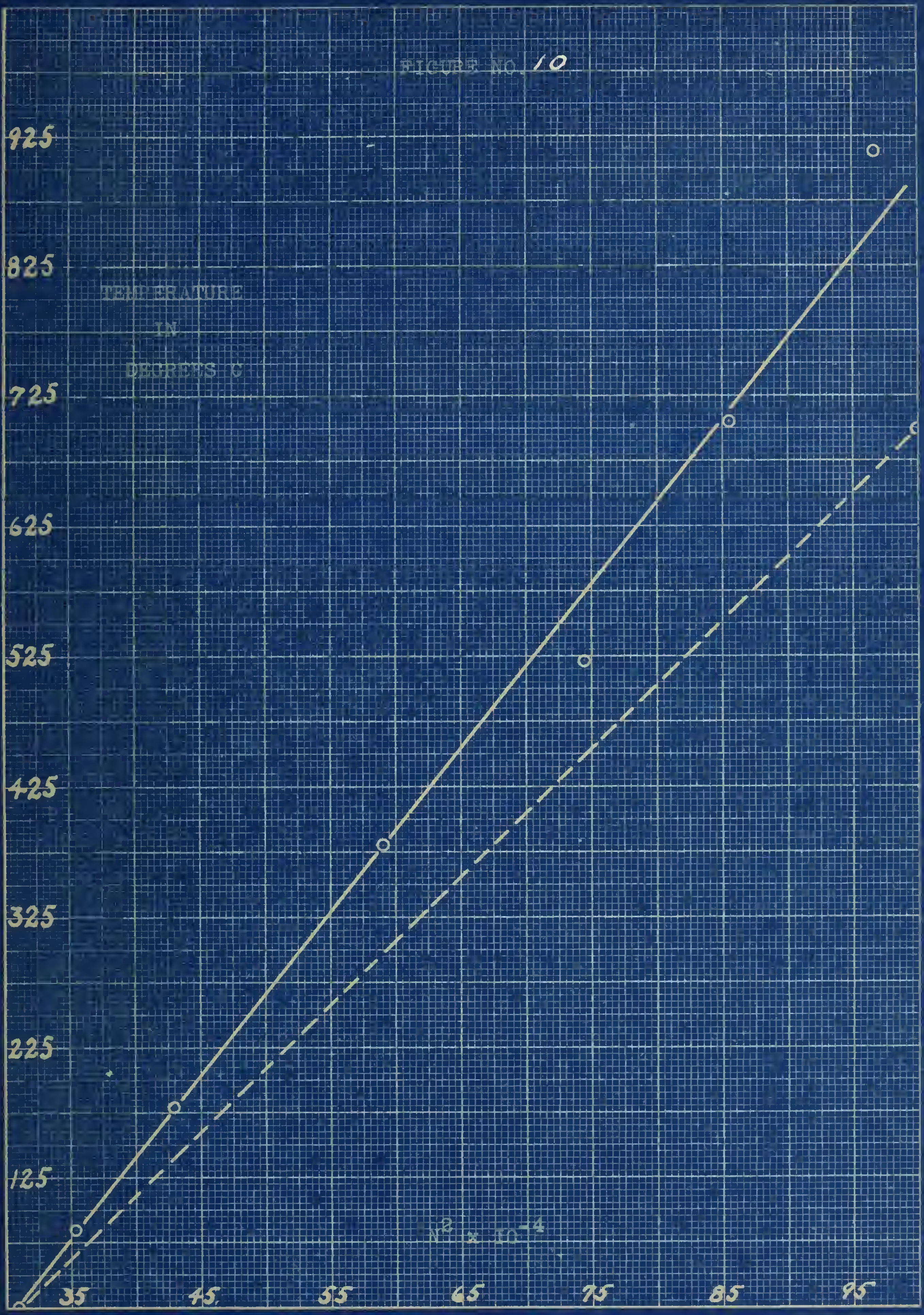


FIGURE NO. 10

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- TABLE NO. II -

N At lowest speed	N At highest speed	A
360	500	8
405	563	9
540	750	I2
450	625	I0
675	938	I5
720	I000	I6
8I0	II25	I8

This table shows the range of the Helmholtz double siren. It will be seen that there may be any pitch produced from 360 to II25 vibrations per second. By slowing down the motor still further, a lower pitch may be obtained. There is a lower gear ratio which it is possible to use, and this lowers the whole range if used. N here signifies pitch, and A as before means the number of holes in the disc.

- CHAPTER 4 -

DISCUSSION OF RESULTS

SUMMARY

DISCUSSION OF RESULTS.- The plotted data in every case, show that the actual results did not coincide with the theory beyond giving a straight line when θ is plotted against N^2. The difference in slope would indicate that the temperature measured with the thermometer and thermocouple was higher than the average actual temperature of the resonator. This however, is what should be expected, for while the theory assumes a constant temperature thruout the tube, it is experimentally very difficult to obtain exactly this condition. By inserting a very thin mica diaphragm in the tube,(7) convection currents were eliminated to some extent. Theoretically, this diaphragm should be placed exactly at the node of the stationary waves in the tube. This position was calculated at room temperature in the following way. Since the end correction is .6 R , this was added to the length of the tube, and the resulting quantity divided by three.The result of this division was subtracted from the total effective length of the tube, which includes the end correction, and the diaphragm placed at this distance from the closed end. This is the theoretical position of the node when the resonator is responding to the first overtone. Experimentally, the correct position was found by inserting the diaphragm in the tube to approximately the correct position, and moving it backward and forward until a maximum deflection of the resonator mirror was obtained.(This at room temperature). The pitch of the siren had been adjusted before the diaphragm had been inserted, so that the resonator responded. The idea of the whole operation was to eliminate convection currents as much as possible without destroying the sensitivity of the instrument.

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(7) - Rayleigh, "Theory of Sound",Vol.II,p 50.

By inserting this diaphragm in the tube, two thirds of the length of the tube was practically free from convection currents, without materially affecting the wave formation. The remaining third of the length, from the diaphragm to the open air, was disturbed by convection currents and conduction to the air, so that the average resultant temperature was lower than that measured by the thermocouple.

Altho this is of theoretical interest, it should not invalidate the apparatus as a means of measuring temperature, as it is calibrated under actual working conditions, and the calibration curve eliminates the necessity for correcting for unequal temperatures in the tube. It may be possible to formulate a correction which would allow the temperature to be calculated knowing only the constants of the instrument, and the pitch to which it would respond at the unknown temperature.

The sensitivity of the apparatus depends on the delicacy of the suspension system. In our apparatus, a decided change in the deflection of the resonator mirror could be observed when the pitch of the siren was changed by an amount, which, ahen reduced to temperature by the calibration surve, corresponded to about 5° Centigrade.

The pitches were determined to within one vibration per second of the actual pitch, and the temperature as obtained by the thermocouple was read to a tenth of a degree Centigrade. The chief source of error was in the determination of the maximum deflection. Since the whole suspension system was subjected to furnace heat, it was very difficult to determine the maximum deflection. The deflection depends on the density of the fluid, and this density

decreases, causing the deflection to decrease. But, since the deflections are entirely independent of each other, the maximum deflection only being desired, there is no cumulative error in the observations.

In improving the apparatus, the first thing to be done is to remove the suspension from the source of heat. To do this, a double resonator will be used, and the disc suspended in the small connecting passage. A small necked resonator will be used, and the effect of the shape, size and temperature of the neck alone will be studied. There are other possible methods which may be tried, the results of which will be produced at a later date.

SUMMARY.- By the use of a Rayleigh resonator, the temperature of which may be varied, the relation between the pitch of the external tone and the temperature of the resonator may be verified experimentally. Improvements are being made in the apparatus in an attempt to apply the theory to a practical temperature measuring instrument.

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